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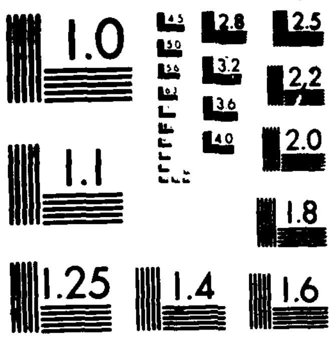

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CENTER FOR
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University of California
Department of Physics
Los Angeles, CA 90024

RF HEATING THE IONOSPHERE

G.J. Morales
Physics Dept., University of California at Los Angeles
Los Angeles, CA 90024-1547

ABSTRACT

A survey of recent developments in the modification of the earth's ionosphere by powerful radio waves is presented from a general perspective of RF heating of plasmas.

MOTIVATION

The study of the interaction of powerful radio waves with the earth's ionosphere enlarges the base for understanding the general problem of heating confined plasmas with RF waves. The earth's ionosphere provides a steady-state plasma in which the electron and ion temperatures are nearly in equilibrium ($T_e \sim 1 - 2T_i$). Due to the large size of the ionosphere and the relatively strong magnetic field of the earth, the ionospheric plasma exhibits good heat confinement. By appropriate selection of the RF frequency, the heated region can be located (say in the F region) far from boundaries. Also, the ionosphere exhibits large low frequency fluctuations analogous to those encountered in laboratory confinement devices, hence the generic problem of RF heating a turbulent plasma is present.

Currently ionosphere heating studies are providing a test ground for modern developments in plasma physics. Relevant examples to the RF community are: mode conversion, electron acceleration and current drive, and beat excitation.

Because the ionosphere is amenable to investigation under widely different plasma environments (e.g., at polar and mid-latitudes) it is possible to explore phenomena which are difficult to isolate in a laboratory device. For instance in the polar ionosphere the density gradient is almost parallel to the magnetic field, thus permitting the study of effects not explored yet in much detail by lab plasma physicists. Other examples of interest are: convective heat transport, memory effects, and transition between collisionless and collisional physics.

Finally, RF heating the ionosphere provides a valuable tool for understanding the fundamental processess that govern the dynamics of the natural ionospheric plasma.

IONOSPHERE PARAMETERS

The experiments of relevance to the RF heating community are those in which the reflection layer for the ground-launched RF wave is located in the F region, which is typically at a height of 250-300 km. In this region the complicated neutral atom chemistry, although important, is not overwhelming. The typical plasma frequency is $\omega_p/2\pi \sim 3$ -10 MHz and the electron cyclotron frequency is $\Omega_e/2\pi \sim 1.4$ MHz.

The electron temperature is $T_e \sim 0.1$ eV and is comparable to the ion temperature, $T_e \sim 1\text{-}2T_i$. At these heights the dominant ion species is O^+ and results in an ion cyclotron frequency $\Omega_i/2\pi \sim 47$ Hz. The collision frequency is dominated by Coulomb processes with a typical ordering 1KHz > $\nu_{ei} \gtrsim \nu_{en}$, with the equal sign holding at the lower heights. The macroscopic density scale length is $L \equiv (d\ln N/dz)^{-1} \sim$ 20-50 km, but shorter scale length distortions are present in the density profile. The electron Larmor radius is ~ 1.5 cm, the ion radius is ~ 250 cm, and the Debye length is $\lambda_D \sim 1$ cm, which implies that $k_D L \sim 10^5$ for these plasmas. The electron distribution function consists of a background Maxwellian plus an energetic photoelectron tail extending to energies of several eV and with a fractional density on the order of 10^{-4}.

ACTIVE EXPERIMENTAL FACILITIES

At the present time there are 3 active RF heating ionospheric facilities in western countries. The Arecibo observatory in Puerto Rico, located at mid-latitude, has been used for RF heating studies for almost 15 years, and its present capabilities are: $P_{RF} \sim 600$ KW, 23 db antenna gain, and frequency range $\omega/2\pi \sim$ 3-10 MHz. The angle between ∇n and $\underline{B}_o$ is on the order of 40^o. At high latitudes the HEATER facility in Tromso, Norway has been operational for nearly 5 years, and its characteristics are: $P_{RF} \sim$ 1MW, 24 db antenna gain, $\omega_{RF}/2\pi \sim 2.5 - 8$ MHz. In Fairbanks, Alaska the HIPAS facility is in operation with $P_{RF} \sim 1$ MW, 17db antenna gain, and $\omega_{RF}/2\pi \sim 4.5$ MHz. The angle between ∇n and $\underline{B}_o$ for these polar facilities is on the order of 13^o.

DIAGNOSTIC CAPABILITIES

The principal diagnostic tool used in ionospheric RF heating experiments is Thomson backscattering from electron plasma waves (plasma line) and from low frequency density fluctuations (ion line). By scattering from the ambient noise spectrum the zero order plasma parameters can be deduced. Scattering from waves enhanced by the RF then permits the study of various nonlinear processes. Recently, Hagfors and his collaborators[1] have developed an ingenious chirping variation of the Thomson scattering diagnostic that permits the identification of short scale density cavities. Other coding schemes used to obtain sharp height resolution are time compression[2] (Duncan and Sheerin) and phase inversion (Barker code) of the Thomson radar pulse. The Thomson radar at Arecibo operates at 430 MHz, and provides information about phenomena having 35 cm wavelength. The equivalent radar at Tromso operates at 933 MHz with bi-static capabilities. Radio-Star scintillations[3] are used to monitor the generation and dynamics of density distortions with scales on the order of 100 meters. Monitoring the enhanced airglow stimulated during RF heating provides information[4] about the integrated distortions produced on the tail of the electron distribution function. A highly desireable diagnostic is the in-situ measurement of wave and plasma parameters inside the heated volume, i.e., the equivalent of inserting a probe in the center of a tokamak plasma. In the ionosphere this can be

accomplished by flying a well instrumented rocket through the RF reflection layer. Due to the high cost and involved logistics of such an operation, few experiments of this type have been performed. In a later section we discuss some interesting results recently obtained from a rocket fly-by in Tromso.

DIFFICULTIES AND UNCERTAINTIES

One of the major obstacles in interpreting the outcome of heating experiments is the highly variable nature of the ionospheric plasma. As a consequence, many experimentalists favor the usage of long time statistical sampling in order to improve the signal to noise ratio. While in some instances this is a worthwhile approach, the danger exists of averaging over completely different physics processes that are triggered under various conditions. For this reason it is useful, when possible, to investigate real-time phenomena with short RF pulses. Because the information about T_e and T_i is derived from Thomson scattering due to thermal fluctuations, it is difficult to obtain meaningful results when the plasma is driven far from equilibrium by the RF. Considerable uncertainty also exists about the actual radiation pattern associated with RF antenna arrays. Idealized calculations are combined with airplane fly-throughs to estimate the actual beam divergence and sidelobe patterns. The situation is somewhat analogous to that encountered in predicting the $k_\parallel$ spectrum of an ICRF antenna in a tokamak. In addition to the antenna uncertainty, the modelling of the RF electric field at the reflection layer is not yet satisfactory. The difficult problem of wave reflection and resonance when $\underline{k}$, ∇n, and $\underline{B}_0$ have arbitrary orientation remains to be solved. Because of the heavy reliance on the Thomson scattering diagnostic, most of the information obtained in heating experiments comes from a narrow height interval and within it from a restricted length scale. Much remains to be learned from the simultaneous usage of several radars having different operating frequencies (e.g., sampling waves at 1-10 meters and at 30 cm).

TOPICS OF PRESENT INTEREST

Research in this area is increasingly being directed toward understanding the connection between microscopic processes, such as generation of electrostatic waves and electron acceleration, and large scale transport modifications. Some of the topics being explored are: role of mode conversion[5], ponderomotive modifications by electrostatic[1,2] and electromagnetic[6] waves, generation of large scale density cavities[7], structure of self-focusing[8], fast electron production[4], stimulated generation of secondary waves[9,10]. A related area of potential interest to the development of communication systems is the controlled generation of low frequency signals[11] (VLF, ELF, ULF) resulting from the modulation of natural ionospheric currents.

RECENT DEVELOPMENTS

Direct Conversion. When a long wavelength electric field of the form $E_0 \exp[i(k_0 z - \omega_0 t)]$ interacts with a nearly static distortion of the density profile $\delta n = \tilde{n} \exp(ikz)$ having $k \gg k_0$, a beat current

$\tilde{j} = (ie^2E_0/m\omega_0)\tilde{n}\exp[i(kz-\omega_0 t)]$ is generated which can excite plasma waves resonantly if Re $\varepsilon(k, \omega_0) \approx 0$. In experiments aimed at examining the response of the ionosphere to short RF pulses [~ 10 msec] it has been found[12] that this process causes a rapid growth of plasma waves which serve as the seed from which nonlinear wave interactions develop. The unique signatures of this process are: no RF power threshold, linear dependence on RF amplitude, instantaneous growth upon arrival of RF, early time secular growth, and frequency centered around ω_0 for nearly static distortions. All of these signatures have been observed experimentally at Arecibo using short RF heating pulses (~ 10 msec) separated by an off-time on the order of 40 msec, and by recording the signals on real time.

Memory Effects. In a follow-up experimental study of direct conversion at Arecibo a paradoxical result has been discovered[13]. It is found that the amplitude of the plasma wave excited within 1-2 msec depends on the length of the RF pulse, i.e., the present behavior depends on the future. Of course, causality is not violated, what actually occurs is that the experiments are performed by firing the RF source repetitively with an off-time on the order of 40 msec. Consequently, the apparent violation of causality is in fact a memory effect, i.e., prior RF pulses are capable of sustaining a high level of irregularities in the density profile that permit the direct conversion process to occur. It is found that a threshold pulse length of 5 msec is required in order for rapid conversion to be observed. For pulse lengths larger than 10 msec direct conversion can be observed for several hours. The sustainment of the process is independet of the average power for $\langle P_{RF}\rangle > 10$ KW. What is of general interest here to RF heating of plasmas is the fact that microscopic RF wave absorption processes are tightly coupled to the global transport properties of the plasma.

Relation to ICRF Heating. Motivated by the ionospheric experiments, an analysis has been made[14] of the direct conversion of ion Bernstein waves resulting from the beat between a fast wave and a drift wave, as may be encountered in a tokamak heating experiment. It is found that this process provides an enhanced damping of the fast wave, which for coherent fluctuations can be significant at a level $|\delta n|/n \sim 1\%$. The process can be a useful high-harmonic heater of large devices, but can also result in the parasitic launching of Bernstein waves by fast couplers, thus giving rise to edge heating. It is expected that some of these processes may be enhanced in plasmas with large edge fluctutations, as is characteristic of compact tokamaks.

Thermal Cavities. In order to assess the connection between microscopic processes and global plasma modifications an Ohmic heating transport code study[7] has been made of a day-time ionosphere. At $P_{RF} = 1$ MW, 20 db antenna gain, a steady-state $\delta T_e/T_e \sim 0.5$ is achieved within 15 sec after RF turn-on. The pressure gradient created at the RF reflection layer causes the growth of a density cavity well beyond the δT_e saturation and having several km in extent. After 10 min the depth of the cavity is $|\delta n|/n \sim 5\%$ and continues to grow as $\sqrt{t}$; an assessment of the relevant recombination chemistry predicts an eventual saturation below the 10% level. Recent experiments at Arecibo performed by Duncan and collaborators, have indeed observed such global density modifications, but the level of

density depletion found can be 50% or larger. Although the details of the underlying physics creating such a large effect have not yet been resolved, it is known that the solar source of plasma must be turned-off, i.e., the observations are made in late-evening experiments. The study of this effect is presently an active topic of research.

Rocket Fly-Through. A rather interesting and technically challenging experiment has been performed by Rose,et al [15] in Tromso. A rocket instrumented with Langmuir probes, magnetic loops, and energy analyzers has been flown through the beam footprint of the ground-launched RF. This rare opportunity at an in-situ measurement has validated the existence of an electromagnetic Airy cut-off, with electron heating emanating from it. Secondary waves and enhanced fast electron tails (energy > $100T_e$) are also detected. Density modifications of the thermal-cavity-type are reported to attain a level $|\delta n|/n \sim 2\%$, consistent with the transport code analysis.

Stimulated Electromagnetic Emissions. An interesting observation by Thide, originally made in Tromso[10], and subsequently repeated in Arecibo, is that when the ionosphere is RF heated, it is stimulated into emitting electromagnetic waves over a rather broad-band (~ 200KHz) centered around the RF heater frequency. Although some of the features in the stimulated emissions could be identified with parametric decay instabilities, the broad and universal character of the emissions has not been yet satisfactorily explained. It is interesting to note that ICRF experiments in JET also exhibit an analogous spontaneous emission. Since early laboratory experiments[16] of electron heating by Landau acceleration have consistently yielded the spontaneous generation of sideband signals, it is suggestive that some of the spontaneous emissions may be related to distortions in the electron distribution function.

Electron Acceleration. To assess the possible role of distortions in the electron distribution function, an analysis has been made[9] of the electron acceleration resulting from localized fields (driven-Airy pattern) excited by mode conversion. Below a threshold electric field the fast electron tail exhibits an unidirectional density enhancement $\delta n_T/n_T = (E_o/E_s)^2$ where $E_s = mv_T{}^2/(e\pi L)$, v_T is the effective tail velocity, and L the density gradient scale length. E_o is the pump field associated with the RF wave, which can be related to the incident power P_o through $E_o = (8\eta P_o/\omega_0 L)^{1/2}$, with η the mode conversion efficiency. Above a threshold field (say $E_o/E_s \sim 6$ for certain ionospheric conditions) the tail distribution develops a region of positive slope. An estimate of the bandwidth of the unstable sideband waves that can be excited by the bump is $\Delta\omega/\omega_o \sim 5 \times 10^{-2}$, which is comparable to the frequency band over which stimulated electromagnetic emissions occur.

Current Modulation. Over the past few years several experimental and theoretical studies have been made of low frequency wave generation by modulating natural ionospheric currents with the RF heating wave, as reviewed in Ref. 11. An analysis[17] of relevance to the RF heating community pertains to the modulation of field aligned currents at frequencies $\omega < \Omega_i$. The formulation allows for the simultaneous excitation of shear and compressional modes by the in-situ antenna generated through thermal modulation of the conductivity tensor. It

is found that 90% of the energy radiated is in the shear mode, and 10% in the compressional, with an efficiency less than 10^{-5}. The shear mode exhibits a collimated headlight-type pattern emanating from the heated region. An analogous behavior has been observed in a tokamak experiment[18] which uses a field aligned wire antenna.

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